American Journal of Industrial Medicine 24:55–66 (1993)

Estimating Historical Exposure to Silica Among Mine and Pottery Workers in the People's Republic of China

M. Dosemeci, PhD, J.-Q. Chen, MD, F. Hearl, SM, R.-G. Chen, MD, M. McCawley, PhD, Z. Wu, MD, J.K. McLaughlin, PhD, K.-L. Peng, MD, A.-L. Chen, MD, S.H. Rexing, MPH, and W.J. Blot, PhD

A quantitative retrospective exposure assessment method was developed for use in a nested case-control study of lung cancer among mine and pottery workers exposed to silica dust in the People's Republic of China. Exposure assessment was carried out in 20 mines (10 tungsten, 6 iron/copper, and 4 tin) and nine pottery factories. A job title dictionary was developed and used in both the collection of historical exposure information and work histories of 1,668 (316 cases and 1,352 controls) study subjects. Several data abstraction forms were developed to collect historical and current exposure information and employees' work histories, starting in 1950. A retrospective exposure matrix was developed on the basis of facility/job title/calendar year combinations using available historical exposure information and current exposure profiles. Information on the amount of respirable, thoracic, and free silica content in total dust was used in estimating exposure to silica. Starting in 1950, 6,805 historical estimates had been carried out for 14 calendar-year periods. We estimated the average total dust concentration to be 9 mg/M^3, with a range from 28 mg/M^3 in earlier years to 3 mg/M^3 in recent years. Several exposure indices [such as cumulative dust, average dust, cumulative respirable (<5 μ in particle size) and thoracic (<10 μ in particle size) silica dust, average respirable and thoracic silica dust, exposure-weighted duration, and the highest/longest exposure] were calculated for individuals by merging work history and historical exposure matrix for each study subject. We developed these various measures of exposure to allow investigators to compare and contrast different indices of historical exposure to silica.

Key words: exposure assessment method, silica, mines, pottery factories

Epidemiology and Biostatistics Program, National Cancer Institute, Bethesda, MD (M.D., J.K.M., W.J.B.).
Department of Labor Health and Occupational Diseases, Tongji Medical University, Wuhan, People's Republic of China (J.-Q.C., R.-G.C., Z.W., K.-L.P., A.-L.C.).
National Institute for Occupational Safety and Health, Morgantown, WV (F.H., M.M.).
Westat, Inc., Rockville, MD (S.H.R.).
Address reprint requests to Mustafa Dosemeci, PhD., National Cancer Institute, 6130 Executive Blvd., Room 418, Rockville, MD 20892.
Accepted for publication October 2, 1992.

INTRODUCTION

Assessment of historical exposure to silica in the dusty trades has been of interest to investigators in occupational epidemiology for decades. Several exposure assessment methods have been developed to study the relationship of silica exposure to silicosis and lung cancer. Some of the methods [Jorgensen, 1973; Fox et al., 1981; Thomas, 1982; Battista et al., 1988] were qualitative and risks were analyzed for ever or never exposure to silica by duration of employment. Some other methods [Higgins et al., 1983; Hessel et al., 1986; Thomas and Stewart, 1987] were semiquantitative and categorized exposure levels as none, low, medium, and high. There were also quantitative methods [Thériault et al., 1974; Rice et al., 1984; Froines et al., 1986; Amandus and Wheeler, 1987; Mastrangelo et al., 1988; Verma et al., 1989] which allowed use of various exposure indices including cumulative exposure, average exposure, and respirable silica exposure.

In this report, we present a quantitative approach to assess historical exposure to silica, using monitoring data for dust and other historical exposure information used in a nested case-control study [McLaughlin et al., 1992] of lung cancer in the People's Republic of China (PRC).

METHODS

Study Background

The study was a collaborative effort by the Tongji Medical University, Wuhan, Hubei, PRC, the National Cancer Institute (NCI), Bethesda, Maryland, and the National Institute for Occupational Safety and Health (NIOSH), Morgantown, West Virginia.

The exposure assessment procedures were carried out for 29 facilities in five provinces of central and south China. Among these facilities, there were ten tungsten mines, eight pottery factories, one clay mine, six iron/copper mines, and four tin mines. All of the mines had underground operations, eight had open-pit mine operations, and twenty had ore dressing operations. There were 57,983 workers in the cohort employed at least one year during the period January 1, 1972 to December 31, 1974. A follow-up of subjects through December 31, 1989 revealed 6,192 deaths. Details of the nested case-control and cohort studies have been reported elsewhere [McLaughlin et al., 1992; Chen et al., 1992].

Procedures Used in the Exposure Assessment Method

Assessment procedures for historical exposures to silica consisted of several data collection and evaluation steps. Figure 1 illustrates the steps used. Description of each assessment procedure follows.

Development of exposure information and work history abstraction forms. A dictionary of job titles was created for five major industrial activity groups (underground mine, open-pit mine, ore separation process, pottery production, and other activities). The same standardized list of job titles was used for both the abstraction of exposure information and for work histories. Job titles in the dictionary were further classified qualitatively, creating one list for silica-exposed jobs and another list for jobs that were not exposed to silica. Silica exposure status of workers was determined by local health authorities, including industrial hygienists who con-

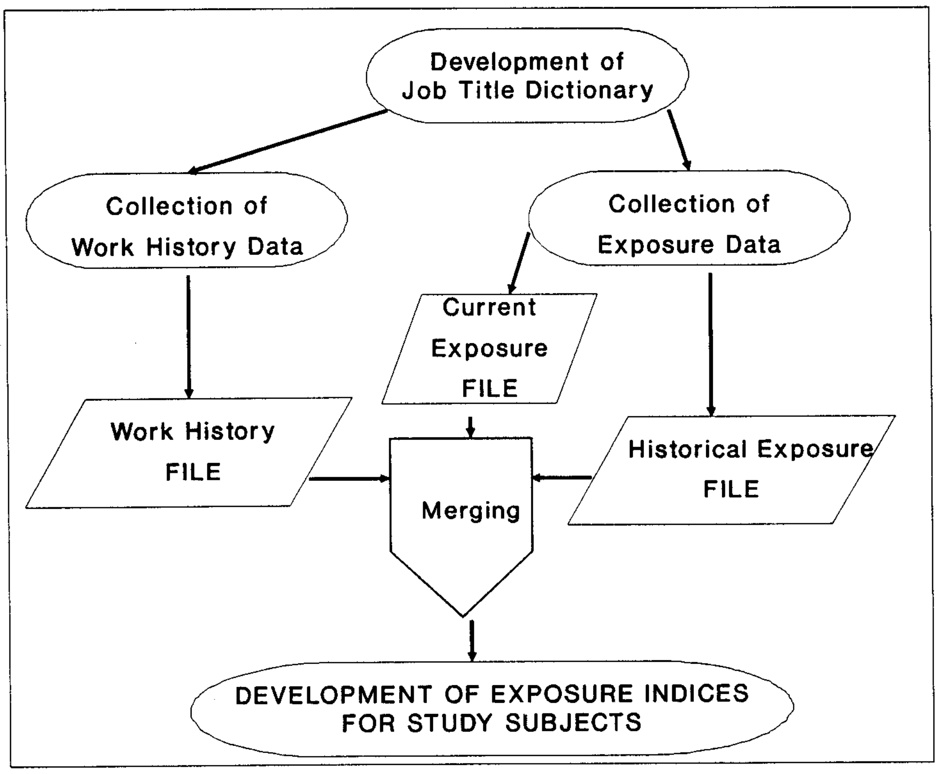

Fig. 1. Steps and procedures in the assessment of historical exposures to silica in study of mine and pottery workers in China, 1950–1987.

ducted the air measurement surveys for silica dust. A sample of job titles from these two lists is presented in Table I.

Four different forms were prepared for the collection of historical exposure data. The first form was designed for the 659 dust-exposed jobs on the basis of facility/job title/calendar year combinations. Altogether, there were 1,392 facility/job title combinations (659 silica-exposed and 733 nonexposed), ranging from 32 to 64 job titles per facility and 14 calendar periods of three-year intervals starting in 1950. Information on the form included the year the job first started at the facility, historical monitoring results for exposure to total dust, number of environmental samples taken, maximum and minimum concentrations of total dust, average exposure hours per day, and other relevant exposure information for each facility/job title/calendar year combination.

The second form was for the collection of more general historical exposure information for the entire facility. The data items for this form included the year the facility first operated, historical changes in the work force (the number of employees by five-year periods), production processes (type and year of changes in the process and their effects on exposure), engineering controls (year of first use and effect of wet dust control and ventilation system on exposure), the use of personal protection equipment (years of respirator use), and other exposure information, such as the first

TABLE I. Sample of Job Titles From Exposed and Nonexposed Job Title Dictionaries in Study of Miners and Pottery Workers Exposed to Silica in China, 1950–1988

Major activity groups	Exposed job titles	Nonexposed job titles
Underground mining	Driller	Water pump worker
	Excavator operator	Signal worker
	Roof control worker	Elevator operator
Open-pit mining	Blaster	Analyst
	Forklift operator	Drying worker
	Transport controller	Gun powder mixer
Ore separation process	Ore unloader	Flotation worker
	Ball mill worker	Ore washer
	Mesher	Crane operator
Pottery production	Crusher	Wet forming worker
	Furnace unloader	Color drawing worker
	Dry forming worker	Pottery packager
Supporting operations	Bricklayer	Carpenter
	Foundry workers	Cook
	Iron casting worker	Welder

year air monitoring was conducted, free silica data, particle size information, and radon gas measurement.

The third form was developed to obtain current silica exposure information, including total dust concentration, percent free silica, respirable (particle size <5 μ) and thoracic (particle size <10 μ) proportion of total dust, and concentrations of the other agents. Information was obtained for three sampling stations (sites) at each of the 29 facilities. Each selected station (sampling site) was sampled for total dust and particle size using cascade impactors under the direction of NIOSH industrial hygienists. For each sampling station, information on personal, area, and bulk sampling was included for each selected station and facility/job title combination.

In addition to exposure forms, a work history abstraction form was designed to collect the lifetime occupational history of each study subject in the case-control study. This form included information on name, sex, date of birth, first and last date of employment, and last employment status of subject. Data on job title names, dates started and stopped, and average number of hours exposed to silica per week for each of the jobs held by the subjects at the study facilities were also included on the form. When available, information on previous employment outside the study facilities was obtained.

Collection of exposure data and work histories. Local industrial hygienists and occupational physicians were trained to collect the exposure information and work histories. During the training, the exposure and work history abstraction forms described above were reviewed item by item. Following the training, all forms were then finalized and data collection was begun for the 29 facilities and for 659 silica-exposed facility/job title combinations.

Starting with 1956, 1,815,742 total dust monitoring records were abstracted for 20 underground mining operations, 72,104 for 10 open-pit mining operations, 221,550 for 20 ore separation operations, and 1,113 for 9 pottery production operations. The Chinese total-dust measurement method is a gravimetric method which is based on area sampling. The dust sampler used is battery operated and collects airborne dust directly onto a pre-weighed filter. Area sampling takes about 20–30 minutes with a flow rate of 20 l/min. Following sampling, the filters are placed in glassine envelopes and sent to the laboratory where they are weighed to determine total dust concentration. Percent silica determinations were performed irregularly and less frequently, starting in 1962 and carried out using the Talvitie method [Talvitie, 1951]; particle size data were limited to the recent years (1980s) only. For the potential confounding exposures, current monitoring results for radon, polycyclic aromatic hydrocarbons (PAH), arsenic, cadmium, nickel, talc, and asbestos were used in the exposure assessment procedures. There were no historical measurements before 1980 for these agents. Details of the assessment methods used for exposure to these confounders are described elsewhere [Wu et al., 1992].

In the second step of the data collection, work histories were collected for 316 lung cancer cases and 1,352 controls from the 29 facilities based on official personnel files, employment records, medical records, long term coworkers, supervisors, and other facility personnel. In addition to the work histories at the facilities, pre-facility employment histories were also collected for each study subject, if available.

Assignment of exposure levels. For each facility/job title/calendar year combination from 1950 to 1987, assignment to seven levels of exposure for total dust (1 = <1 mg/M^3; 2 = 1–1.9 mg/M^3; 3 = 2–5.9 mg/M^3; 4 = 6–9.9 mg/M^3; 5 = 10–14.9 mg/M^3; 6 = 15–24.9 mg/M^3; and 7 = 25+ mg/M^3) was made by the local industrial hygienists and occupational physicians using all available historical exposure data. Assessment of exposure was carried out for 6,805 dust-exposed facility/job title/calendar year combinations. On average, 51.5% of the total dust estimates for all facility/job title/calendar year combinations were based directly on monitoring data; the proportion was higher in more recent years than in earlier years, ranging from 3.1% of estimates for the 1950–1952 period to 73.9% for the 1984–1986 period. For some combinations, there were very few monitoring data, and for a few jobs there were no monitoring data at all. In these situations, estimates of exposure levels were derived from the monitoring data for similar jobs (jobs in the same activity unit, such as other transportation jobs, or other maintenance jobs) or data for the same job from adjacent time periods, with adjustment for the other historical exposure information (changes in production processes, control measures, etc.) and task descriptions of the job titles. Because of incomplete data, estimates of percentage of free silica and respirable dust and levels of exposure to radon, PAH, arsenic, nickel, and cadmium were carried out semiquantitatively only at the facility level.

Verification of estimates using exposure information. All completed forms were sent to the data processing center at the Tongji Medical University in Wuhan, where they were manually edited for completeness and computerized by double keying. Logic and range checks for the computerized data were carried out using a specially developed machine editing program. Verification of exposure estimates developed by local investigators was performed using several consistency check programs. Discrepancies between exposure estimates and the exposure information were evaluated individually, and final decisions on the estimates were made by the industrial hygienists from Tongji Medical University, NCI, and NIOSH.

Development of current exposure matrix. A matrix for current (1988) exposure was constructed using total dust and other monitoring data obtained during the industrial hygiene surveys carried out in 29 facilities [Wu et al., 1992]. In this matrix,

TABLE II. Samples of Estimates of Total Dust From the Historical Exposure Matrix File in Study of Miners and Pottery Workers Exposed to Silica in China, 1950–1988

		Estimates of total dust by calendar-year periods[a]														
Facility #	Job titles	'50 –52	'53 –55	'56 –57	'58 –59	'60 –62	'63 –65	'66 –68	'69 –71	'72 –74	'75 –77	'78 –80	'81 –83	'84 –85	'86 –87	Current ('88)
12	Ore unloader	7	7	7	7	6	6	6	6	6	5	5	4	4	3	3
12	Mesher	5	5	5	5	5	4	4	4	4	4	4	3	2	2	2
22	Crusher	7	7	7	6	6	6	5	5	5	4	4	3	3	2	2

[a]1 = <1 mg/M^3; 2 = 1–1.9 mg/M^3; 3 = 2–5.9 mg/M^3; 4 = 6–9.9 mg/M^3; 5 = 10–14.9 mg/M^3; 6 = 15–24.9 mg/M^3; 7 = 25+ mg/M^3.

levels of exposure to total dust were presented for each sampling station; and job titles at these stations were listed together with the exposure levels. In addition to exposure levels for total dust, the matrix included the amount of respirable and thoracic content of total dust, free silica content in the dust, and concentrations of possible other occupational lung carcinogens (asbestos, radon, PAHs, arsenic, nickel, cadmium, and talc).

Development of historical dust exposure matrix. A historical dust exposure matrix was developed for the facility/job title/calendar year combinations that were found in the work histories of 316 cases and 1,352 controls. In this matrix, estimates of total dust exposure were listed along with specific facility/job titles for 14 time periods during 1950–1987 (Table II). Information from the current (1988) dust exposure matrix was used to evaluate the estimates in the historical dust exposure matrix for the last calendar period (1985–1987). For percentage of free silica and respirable/thoracic proportions of the total dust, medians of both historical and current measurement results were calculated over all jobs and time periods for each facility. These median values for each facility were used, rather than each facility/job title/calendar year combination, because of the lack of historical exposure information at the job title level. The matrix was merged with work histories to calculate exposure indices for each study subject.

Development of subject's work history file. A subject's work history file was created for use in the calculation of exposure indices. Two samples are presented in Table III. In this file, all the jobs held by the subject were listed with date started and date stopped for each job. The same facility and job code systems were used in this file and in the historical dust exposure matrix to allow proper linkage between the file and the matrix.

Calculation of exposure indices. Four major exposure indices were calculated (cumulative dust exposure, average dust exposure, cumulative respirable silica exposure, and cumulative thoracic silica exposure) in addition to other exposure indices. Of the major exposure indices, two were for total dust exposure and the other two for free silica exposure. Calculations of these indices were as follows:

Cumulative total dust exposure ($E_{cum\text{-}tot\text{-}dust}$). For each study subject, cumulative dust exposure was calculated using the following equation:

$$E_{cum\text{-}tot\text{-}dust} = \sum_{j=1}^{n} C_j \times T_j$$

TABLE III. Samples From Work History Files in Study of Miners and Pottery Workers Exposed to Silica Dust in China, 1950–1988

Worker ID	Job #	Facility #	Job title	Date started	Date stopped
Worker A	1	12	Ore unloader	1965	1970
	2	12	Mesher	1971	1978
	3	12	Ore washer (nonexposed)	1979	1982
Worker B	1	22	Crusher	1955	1969
	2	22	Wet forming worker	1970	1976

where n = number of job (j) combinations held by the subject in the work history, C_j = total dust concentration for the facility/job combination and employment period (from the historical dust-exposure matrix), and T_j = duration of employment of subject for the job (j) (from work history file; adjusted by the number of hours worked per day).

For example, for subject A, whose work history is presented in the first part of Table III, cumulative total dust exposure was calculated using exposure levels from Table II and duration of employment from Table III:

$$\begin{aligned} & \qquad\quad \text{Job \#1} \qquad\qquad\qquad \text{Job \#2} \qquad\qquad\qquad \text{Job \#3} \\ E_{\text{cum-tot-dust}} &= (20\ \text{mg/M}^3 \times 6\ \text{yrs}) + (8\ \text{mg/M}^3 \times 8\ \text{yrs}) + (0\ \text{mg/M}^3 \times 4\ \text{yrs}) \\ &= 184\ \text{mg/M}^3 - \text{year}. \end{aligned}$$

Average total dust exposure ($E_{ave\text{-}tot\text{-}dust}$). An average dust exposure level for each study subject was calculated using the level of cumulative dust exposure and the total duration of exposure as follows:

$$E_{\text{ave-tot-dust}} = E_{\text{cum-tot-dust}} / D_{\text{exposed}},$$

where D_{exposed} is the total duration of exposed period.

For example, for worker A:

$$E_{\text{ave-tot-dust}} = (184\ \text{mg/M}^3\text{-year}) / (14\ \text{year}) = 13\ \text{mg/M}^3.$$

Note that the four years of no exposure were not included in total duration of exposure.

Cumulative respirable silica exposure ($E_{cum\text{-}res\text{-}silica}$). This exposure index was calculated using cumulative total dust exposure and the percentages of the respirable part of the total dust ($\%_{\text{res}}$) and the silica content of the total dust ($\%_{\text{silica}}$). Note that, in our study, percentages of respirable dust and silica content were for facility levels only, due to the lack of specific measurements for job titles. The formula used in the calculation of this index was as follows:

$$E_{\text{cum-res-silica}} = (E_{\text{cum-tot-dust}}) \times (\%_{\text{res}}) \times (\%_{\text{silica}}).$$

For the calculation of cumulative respirable silica exposure for subject A, median percentages of respirable dust and silica content were 75 and 29, respectively, for facility #12:

$$E_{\text{cum-res-silica}} = (184 \text{ mg/M}^3\text{-year}) \times 0.75 \times 0.29 = 40 \text{ mg/M}^3\text{-year}.$$

Cumulative thoracic silica exposure ($E_{cum\text{-}tho\text{-}silica}$). This index is similar to the index of cumulative respirable silica exposure, but in this index the median of the percentage of thoracic dust ($\%_{\text{tho}}$) was used instead of the respirable dust percentage:

$$E_{\text{cum-tho-silica}} = (E_{\text{cum-tot-dust}}) \times (\%_{\text{tho}}) \times (\%_{\text{silica}}).$$

For subject A, the median of the percentage of thoracic dust in facility #12 was 90. Thus,

$$E_{\text{cum-res-silica}} = 184 \text{ mg/M}^3\text{-year} \times 0.90 \times 0.29 = 48 \text{ mg/M}^3\text{-year}.$$

Other exposure indices. In addition to the above basic exposure indices, the following indices were also calculated.

1. Average Respirable Silica Dust: The medians of the percentage of respirable dust and the percentage of silica are multiplied by $E_{\text{ave-tot-dust}}$.
2. Average Thoracic Silica Dust: The medians of the percentage of thoracic dust and the percentage of silica are multiplied by $E_{\text{ave-tot-dust}}$.
3. Cumulative Respirable Dust: The median of the percentage of respirable dust is multiplied by $E_{\text{cum-tot-dust}}$.
4. Average Respirable Dust: The median of the percentage of respirable dust is multiplied by $E_{\text{ave-tot-dust}}$.
5. Cumulative Thoracic Dust: The median of the percentage of thoracic dust is multiplied by $E_{\text{cum-tot-dust}}$.
6. Average Thoracic Dust: The median of the percentage of thoracic dust is multiplied by $E_{\text{ave-tot-dust}}$.
7. Cumulative Silica: The median of the percentage of silica content is multiplied by $E_{\text{cum-tot-dust}}$.
8. Average Silica: The median of the percentage of silica content is multiplied by $E_{\text{ave-tot-dust}}$.
9. Exposure-Weighted (across all jobs by facilities) Duration: Average of the total dust measurement results across all jobs at each facility is multiplied by the duration of exposure for the subject at that facility.
10. Exposure-Weighted (across all facilities by jobs) Duration: Average of the total dust measurement results across all facilities by each job title is multiplied by the duration of employment at that job.
11. Semiquantitative Exposure Assignment by Job (cumulative): One of the semiquantitative exposure levels (none, low, medium, high) is assigned for each job title in the study, regardless of facilities. Exposure weights are assigned for level (0, 1, 4, 12, respectively) to calculate the cumulative exposure for the subject.
12. Semiquantitative Exposure Assignment by Job (average): In this index, the semiquantitative exposure assignment by job (cumulative) is divided by the duration of exposure for the subject.
13. The Highest/Longest Exposure: The same semiquantitative exposure levels are

TABLE IV. Distributions of Several Exposure Variables by Calendar Periods in the Study of Miners and Pottery Workers Exposed to Silica in China, 1950–1988

	Calendar-year periods														
Exposure variables	'50 –52	'53 –55	'56 –57	'58 –59	'60 –62	'63 –65	'66 –68	'69 –71	'72 –74	'75 –77	'78 –80	'81 –83	'84 –85	'87 –88	All yrs
Number of estimates	98	275	327	420	463	501	515	596	602	601	603	610	597	597	6805
% Estimate of dust meas.	3	2	7	24	30	49	52	46	62	61	68	74	74	69	52
% Estimate of SiO_2 meas.	13	3	1	10	8	13	5	9	19	23	10	14	37	17	14
Mean dust est. (mg/M^3)	28	23	20	9	7	5	4	4	4	4	4	3	3	3	9
Mean dust meas. (mg/M^3)	96	64	91	6	3	4	3	7	4	4	3	3	3	3	21
% Est. based on records	2	1	6	24	30	48	51	46	60	60	67	73	72	68	51
Mean # of hr/day	6.5	6.2	6.1	5.7	5.5	5.4	5.0	4.7	4.8	4.9	4.9	4.9	4.9	4.8	5.1

assigned for the job titles, regardless of facilities, but this time instead of weight assignments, the exposure level of the highest/longest exposed job held by the subject is used as the exposure level for the subject.

Indirect validation of exposure estimates. In order to evaluate the validity of our exposure estimates, we examined the relationship between silica exposure and silicosis in the cohort of workers. Risk of silicosis was measured using the odds ratio, an estimate of relative risk, for each level of silica exposure. Odds ratios for cumulative respirable silica dust were 1.0, 6.4, 26.3, and 66.7 for none, low, medium, and high exposure categories, respectively.

RESULTS

Table IV presents the distribution of exposure variables used in the retrospective assessment of exposure to silica dust for all subjects regardless of their job titles and facility types. Starting with 1950, 6,805 historical estimates were carried out for 14 calendar-year periods. Average percentage of estimates based on environmental measurements was 52, ranging from 2% for very early years to 74% for recent years. Although percentage of total-dust estimates based on monitoring data was quite high, only 14% of silica dust estimates was based on free silica measurement. The results for estimated total dust exposure are presented in the fourth row. Average estimated total dust concentration was 9 mg/M^3, ranging from 28 mg/M^3 for earlier years to 3 mg/M^3 for recent years. Average working hours per day over the periods were 5.1, ranging from 6.5 hours for the earlier to 4.7 hours for the recent years. Overall, 51% of the dust estimates were based on the written records, increasing from 1% for early years to 73% for recent years.

DISCUSSION

We have presented an approach for the historical assessment of silica exposure among miners and pottery workers in China using a nested case-control study of lung cancer. This study was a unique large-scale multicenter investigation based on more than two million measurement values. Quantitative retrospective exposure assessment is a challenging task and has been less frequently used in occupational epidemiology. There is no generic assessment method that can be applied for all types of epidemiologic studies. Each study design requires customized assessment methods, determined by the availability of historical exposure information. The accuracy and validity of the assessment method mainly depend on the quality of the available historical exposure information. Often, there are very few historical records available for the earlier years. In these situations, the challenge is to develop appropriate mechanisms to extrapolate recent exposure information to the earlier years. In this study, we proposed several sets of mechanisms which may be used as examples for future assessment methods that would need to be developed for similar study designs.

There are several strengths and weaknesses of the method used in this study. The strengths of the study include the large number of facilities, study subjects, and monitoring data for the historical dust exposure, and the fact that workers in the PRC generally have fewer lifetime jobs than workers in Western nations [Stewart et al., 1986, 1991]. The homogeneity of exposure history, therefore, was higher in this study than in occupational studies in Western countries. Another strength of the study is the easy access to factory records, including monitoring, personnel, and health records. This feature of the study was valuable not only for obtaining epidemiologic data, but also in obtaining historical exposure information for the retrospective exposure assessments.

Although there were 2.1 million monitoring results for total-dust exposure, very few direct measurements were available for the percentage of silica and respirable/thoracic fraction of the total dust. The quality and amount of historical information on total dust concentration were quite remarkable, particularly after the period of 1963–1965, and this feature of the exposure data allowed us to employ a detailed job-title specific exposure assessment to estimate total dust concentration. Unfortunately, information on the silica content of total dust and percentage of respirable and thoracic dust was limited to recent years and to a few jobs. Therefore, it was decided to develop an average value for each facility, rather than for each specific job for these exposure variables, assuming that the proportion of these variables in the total dust did not vary much over time and across job titles. The authors are aware that this assumption is not necessarily correct. However, given the available exposure data and the restrictions of the study, this approach appeared to be the most plausible.

Similar assumptions and decisions were made for the confounding exposures (radon, PAHs, arsenic, cadmium, nickel), due to the quality and the quantity of information. The other weakness of this approach is the use of a job title dictionary in coding the jobs in the facilities and in the subjects' work histories. Such standardization, however, was the only practical way to deal with the thousands of various job titles that existed in five major industrial activity groups. The use of an a priori job title dictionary may not have a large effect in our study because the dictionary was developed after a review of original job titles, and the same Chinese investigators who developed the dictionary carried out the occupational coding.

The gradient of the dose-response relationship between silica estimates and silicosis clearly indicates that the retrospective assessment of silica exposure used in our investigation was satisfactory, as it demonstrated the known strong dose-response relationship between silica and silicosis. We are aware of the fact that this indirect validation was based on several assumptions, such as 1) there is a real dose-response relationship between silica exposure and silicosis; 2) the selected study population is representative to reflect this association; 3) diagnosis of silicosis is adequate to observe this association; and 4) misclassification of exposure is nondifferential and direction of the distortion is towards the null. Because we observed a strong association between silica estimates and silicosis, it is not unrealistic to presume that these assumptions are more or less valid; otherwise it would be unlikely to observe such a strong dose-response relationship between exposure and disease.

In summary, the approach described here is the first attempt to retrospectively assess silica exposure using almost 7,000 facility/job title/calendar-year-period combinations and 2.1 million historical dust measurements. It was a challenge to coordinate all current and historical exposure information with the work histories of the subjects in this multicentered and multi-industry study population. Several features were introduced in the exposure assessment procedures, including the use of an industry-based job title dictionary; the collection of exposure information at facility and facility/job title/calendar year levels; the coordination of work history and exposure data collection on the basis of the job title dictionary; and the development of several exposure indices to be examined in the epidemiologic analyses. These features, we believe, made the silica exposure assessment more sensitive and accurate.

REFERENCES

Amandus HE, Wheeler R (1987): The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite. Part I. Exposure estimates. Am J Ind Med 11:1–14.

Battista G, Belli S, Carboncini F, Comba P, Levanta G, Sartorelli P, Strambi F, Valantini F, Axelson O (1988): Mortality among pyrite miners with low-level exposure to radon daughters. Scand J Work Environ Health 14:280–285.

Chen JQ, McLaughlin JK, Zhang JY, Stone BJ, Luo JM, Chen RA, Dosemeci M, Rexing SH, Wu Z, Hearl FJ, McCowley MA, Blot WJ (1992): Mortality among dust-exposed Chinese mine and pottery workers. J Occup Med 34:311–316.

Fox AJ, Goldblatt P, Kinlen LJ (1981): A study of the mortality of Cornish tin miners. Br J Ind Med 38:378–380.

Froines JR, Wegman DH, Dellenbaugh CA (1986): An approach to the characterization of silica exposure in U.S. industry. Am J Ind Med 10:345–361.

Hessel PA, Sluis-Cremer GK, Hnizdo E (1986): Case-control study of silicosis, silica exposure, and lung cancer in white South African gold miners. Am J Ind Med 10:57–62.

Higgins ITT, Glassman JH, Oh MS, Cornell RG (1983): Mortality of Reserve Mining Company employees in relation to taconite dust exposure. Am J Epidemiol 118:710–719.

Jorgensen SH (1973): A study of mortality from lung cancer among miners in Kiruna 1950–1970. Work Environ Health 10:126–133.

Lynge E, Kurppa K, Kristofersen L, Malker H, Sauli H (1986): Silica dust and lung cancer: Results from the Nordic occupational mortality and cancer incidence registers. JNCI 77:883–889.

Mastrangelo G, Zambon P, Simonato L, Rizzi P (1988): A case-reference study investigating relationship between exposure to silica dust and lung cancer. Int Arch Occup Environ Health 60:299–302.

McLaughlin JK, Chen JQ, Dosemeci M, Chen RA, Rexing SH, Wu Z, Hearl FJ, McCawley AM, Blot WJ (1992): A nested case-control study of lung cancer among silica-exposed workers in China. Br J Ind Med 49:167–171.

Rice C, Harris RL, Lumsden JC, Symons MJ (1984): Reconstruction of silica exposure in the North Carolina dusty trades. Am Ind Hyg Assoc J 45:689–696.

Stewart AP, Blair A, Cubit D, Bates RE, Kaplan SA, Ward J, Gaffey W, O'Berg M, Walrath J (1986): Estimating historical exposures to formaldehyde in a retrospective mortality study. Appl Ind Hyg 1:34–41.

Stewart PA, Lee JS, Marano DE, Spirtas R, Forbes CD, Blair A (1991): Retrospective cohort mortality study of workers at an aircraft maintenance facility. II. Exposures and their assessment. Br J Ind Med 48:531–537.

Talvitie NA (1951): Determination of quartz in presence of silicates using phosphoric acid. Anal Chem 23:623–626.

Thériault GP, Burgess WA, DiBerardinis LJ, Peters JM (1974): Dust exposure in the Vermont granite sheds. Arch Environ Health 28:12–17.

Thomas TL (1982): A preliminary investigation of mortality among workers in the pottery industry. Int J Epidemiol 11:175–180.

Thomas TL, Stewart PA (1987): Mortality from lung cancer and respiratory disease among pottery workers exposed to silica and talc. Am J Epidemiol 125:35–43.

Verma DK, Sebestyen A, Julian JA, Muir DCF, Schmidt H, Bernholz CD, Shannon HS (1989): Silica exposure and silicosis among Ontario hard rock miners. II. Exposure estimates. Am J Ind Med 16:13–28.

Wu Z, Hearl F, Peng KL, McCawley M, Chen AL, Palassis J, Dosemeci M, Chen JQ, McLaughlin J, Blot W (1992): Current exposure levels in Chinese iron and copper mines. Appl Occup Environ Hygiene. 7(11):735–743.